

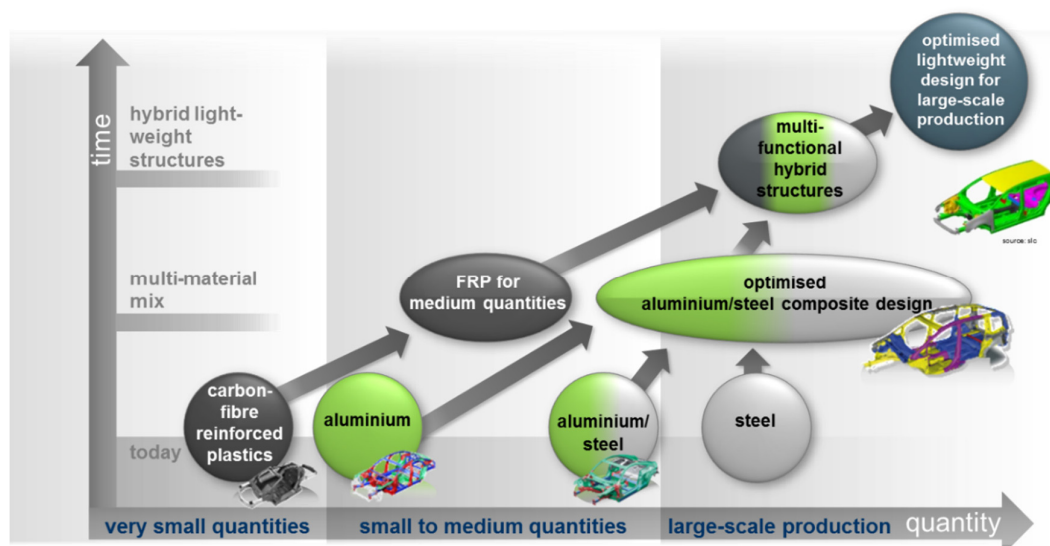
## TOWARDS KNOWLEDGE BASED ENGINEERING FOR MULTI-MATERIAL-DESIGN

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### 1. Introduction

Vehicle comfort, safety and driving dynamics are continuously rising customer demands which once led to increasing vehicle weight. Today, this trend has stopped as a result of new vehicle concepts and the use of lightweight materials such as light metals, high strength steel or fibre reinforced plastics (FRP). That is why vehicle weight is now aimed to keep at a constant weight level, especially for vehicles with conventional drivetrains. However, taking into account future automotive standards in quality, ecology and economy, this lightweight trend must be reinforced [Nehuis et al. 2013]. The combination of FRP as well as metallic materials will be referred as multi-material or hybrid design in this paper. Such a combination of FRP together with steel or aluminium is unavailable for mass production at this point in time. This is caused by the high cost of fibre materials as well as by the extensive process time of producing fibre reinforced components.



**Figure 1. Strategy to enable new lightweight potential in the automotive industry, modelled after [Täger and Plath 2013]**

Nevertheless, the production of hybrid structures together with fibre reinforced parts is said to be more useful for mass production. Figure 1 above illustrates today's vehicle body concepts with regard to the

producible quantities and shows possible ways to optimise lightweight vehicle body concepts for large-scale production [Fischer et al. 2014].

Besides lightweight design one goal in the course of vehicle development is the improvement of its environmental performance within the product life cycle. This is typically reflected by break-even calculations based on life cycle assessment, e.g. [Broch et al. 2015]. Environmental hotspots for products in multi-material-design are shifting from the use phase to the raw materials extraction, manufacturing and end-of-life phase. This is caused by a larger demand for energy and resources in the respective phases. Recent studies indicate that for car body components especially the use of carbon fibre reinforced plastics (CFRP) leads to significantly higher primary energy demands compared to steel or aluminium alternatives. The use phase energy savings through weight reduction may only compensate these additional impacts when intelligently leveraging the CFRPs mechanical advantages in component design [Dufloy et al. 2012].

## **2. State of art**

The state of research is divided into three sections: The first section deals with a methodological approach to multi-material-design, the second section summarises the application of multi-material components in automotive industry while the third section recapitulates the fundamentals of knowledge based engineering.

### **2.1 Methodological approach to multi-material-design**

In general, the product design process can be divided into five phases [Pahl et al. 2007]. The product design begins with the clarification of the development task and the determination of the product requirements. There are various approaches for the determination of requirements, such as questionnaires and checklists. Requirements include functions and features of the components, for instance mechanical behaviour.

In the course of the conceptual design phase functions are further specified and first solution principles are found. During the conceptual design the material selection is crucial because the desired functions are only realised by combining a geometry concept with the chosen material, for example the components bending stiffness is a function of the moment of inertia and the Young's modulus. In addition, solution principles and material selection are often dependent.

An overview of material selection methods is given by [Ashby et al. 2004] and [Jahan et al. 2010]. The main finding is that today methods are limited to two or three material selection criteria. This is why multi-criteria decision approaches seem promising. Additionally, specific approaches especially for material selection in multi-material-design have been defined by [Giaccobi et al. 2010], where the material is selected for each function individually. After conceptual design, the product is embodied by generating 2D and 3D geometry. During embodiment design 3D product models are generated which are used for further analysis such as packaging and assembly tests or numerical simulation of the mechanical behaviour. While the stage of detailed design, the product data is refined for manufacturing and optimised for better mechanical performance or decreasing weight and costs. The product design process is finalised with the generation of product documentation including technical drawings and product manuals.

### **2.2 Design of multi-material components in automotive applications**

Conventional materials and design approaches like geometry optimisation and material substitution have their limits. That is why new lightweight design strategies are taken into account. A promising approach is the multi-material-design which is characterised by load and function specific interaction of different materials within one component. There are various applications and perspectives for components in multi-material design in the automotive industry. In most cases, the application of plastics for large-scale production is limited to components with low level exposure (e.g. interior trim, fenders, tailgates, front-end modules). Nowadays, higher loaded plastic components are implemented as a result of using short fibres as composites in large-scale production. For FRP parts, which meet or exceed the properties of metallic materials, applicable manufacturing processes are limited to small quantities. Thermoplastic prepreps such as organic sheets are only used for expensive vehicle classes for example in the rear seat

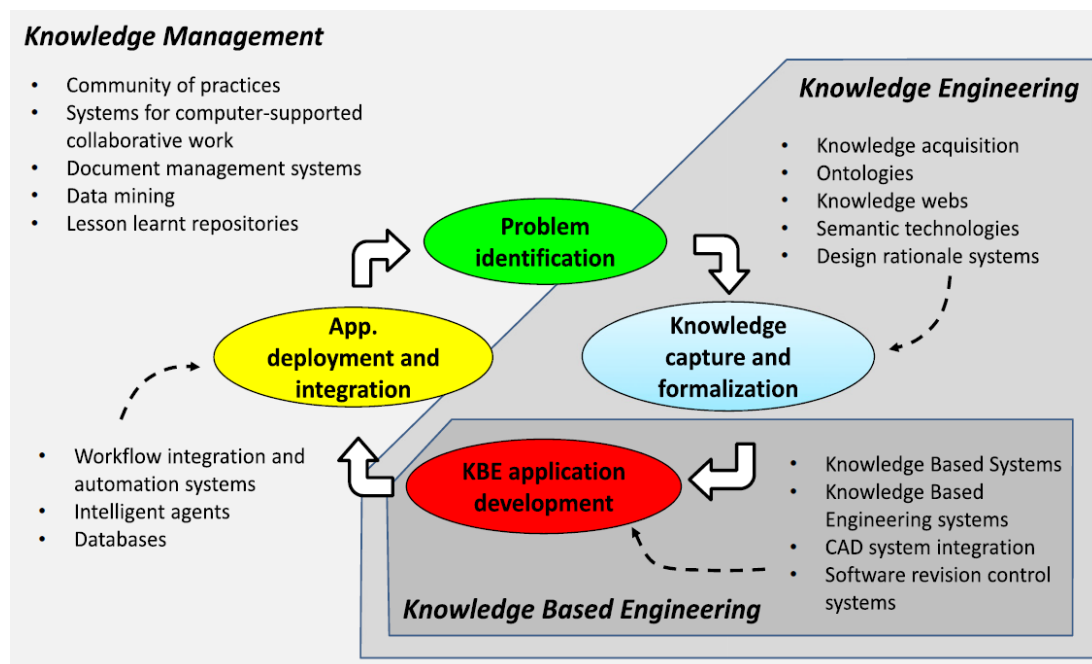
structure and the crash management system of the BMW M3. For structural components in multi-material-design new vehicle concepts (e.g. BMW i Concept) are pursued which require new assembly process chains and infrastructures.

Other applications aim for material substitution for large-scale production with the goal of conventional vehicle concepts and components (e.g. SuperLIGHT-Car) [Goede et al. 2009]. The application of multi-material-design influences the shape of components and entire products which, in turn, affects the production processes. An integration of multi-material-components in current process chains is indispensable to achieve large-scale producibility. In this case, the joining and production technologies affect the components' requirements significantly.

The multi-material-design has great potential for weight reduction in vehicle design, but there are currently no manufacturing processes for large-scale production available. Moreover, the design of multi-material components needs to be facilitated due to the complex relations of technical, ecological and economic development goals [Kleemann and Vietor 2015]. Furthermore, for developing automotive components in multi-material-design, extensive expertise for various topics is compulsory. Besides, design expertise regarding steel and aluminium, knowledge about FRP, joining and production technologies are crucial.

### 2.3 Knowledge Based Engineering

The objective of Knowledge Based Engineering (KBE) is to reduce time and costs of new product development. This is primarily achieved by automation of repetitive design tasks while capturing, retaining and re-using product and process knowledge [Liese 2004]. In recent years, KBE methodologies, technologies and systems have been developed that facilitate new product development taking into account product life-cycle requirements, constraints and knowledge.



**Figure 2. Relative positioning of knowledge based engineering, knowledge engineering and knowledge management. Lists of knowledge technologies involved in the various phases of the development process of a KBE application for engineering design [LaRocca 2012]**

The provision of knowledge in Computer Aided Systems (CAx-Systems) at an early stage of the development process enables the engineer to a reasonable decision-making and completes the digital data in terms of the product life-cycle. By collecting knowledge of products, processes and organisational requirements in a knowledge management system, the development of new and innovative products is facilitated [Vajna et al. 2009].

As a result of automation of repetitive and non-creative assignments, KBE offers an optimisation of the design process by relieving the engineer and therefore reduce costs. According to La Rocca, preliminary steps to KBE are Knowledge Management (KM) and Knowledge Engineering (KE). KM is shown as the comprehensive area where the focus on the overall goal of promoting and supporting initiatives can enable a more efficient and effective use of knowledge assets in the organisation. The research discipline of KE can be seen as a subset of KM. It concentrates on the acquisition and formalisation of knowledge to support the development, implementation and maintenance of Knowledge Based Systems (KBS), which is supported by various methodologies e.g. common knowledge acquisition and documentation structuring (CommonKADS), model-based and incremental knowledge engineering (MIKE) and Protégé-II [Kuhn et al. 2011]. KBS use a formalised set of knowledge to offer problem-solving advice or to solve problems directly. KBS typically include acquisition mechanisms, a structured knowledge base containing a body of domain knowledge and reasoning mechanisms to solve the problems at hand. As such, KBS typically contain the two main elements used to formally represent knowledge: ontology and logic. Ontology can be defined as an explicit conceptualisation of a domain, representing a structured view of the concepts and relationships in a domain - similar to the definition of information as data within a structured context. The concepts and relationships of an ontology are often expressed using formal language, such as predicate logic, which enables the construction of structured knowledge bases upon which logical operations (inferences) can be performed through reasoning mechanisms. Ideally, the KBS capabilities regarding knowledge capture, knowledge representation and reasoning are to be merged with computer-aided design (CAD) and computer-aided analysis (CAA) capabilities to provide engineers with automated assistance in geometry manipulation, data processing and analysis [Stjepandić et al. 2015].

Based on KBS and its identified and formalised knowledge, KBE is an extension which enables the manipulation of geometry or assemblies in CAD. KBE systems are used as general tools to develop KBE applications through a programming approach using KBE programming languages. Applying such an approach, the application of KBE to automate routine design tasks has resulted in significant savings as well as faster and more flexible exploration of the design space [Verhagen et al. 2012]. The integration of KM to CAD systems is possible in two ways. First, there is an extended programming interface with the functionality of an AI language. This way it is possible to create user-defined KBE applications like any other CAD application in a software development process. Thus, expert knowledge of software development is needed which lack most CAD users. As this approach is very complicated and risky for most enterprises, many additional commercial KBE modules are offered, in which KBE templates can be created interactively in software development without expert knowledge. Nowadays, there are 'KBE-like' functionalities available for every major CAD system such as CATIA by Dassault Systemes, NX by Siemens or Creo by PTC. Furthermore, both approaches can be combined with each other and with the application programming interface (API) additional tools can be integrated in a KBE process. Contrary to a KBE application which consists of an executable software code which has to be installed at every workstation, a KBE template consists of one or more CAD models which have to be instantiated by use. Templates and user-defined features offer an acceleration of the development task and a reduction of repetitive modelling tasks by automation of engineering tasks.




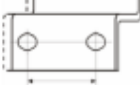

### **3. Manual Multi-Material-Design**

For developing automotive components in multi-material-design extensive expertise for various topics is compulsory. To accelerate the development of components in multi-material-design and to enhance the engineers' expertise, a Knowledge Management System must be developed.

There is already a large amount of knowledge in various fields shown in a wide range of publications [Pahl et al. 2007], [Schürmann 2007], [Klein 2013], Composites Part A and B, Acta Mater. This knowledge is commonly tailored to specific applications and industries and cannot be directly applied to automotive engineering. One major industry using FRP and advanced lightweight design is the aerospace sector. Unfortunately, the design standards for aviation are not suitable for the automotive sector due to their high costs, long production time and high quality management [Kleemann and Vietor 2014]. Nevertheless, the knowledge management system should contain general regulation for lightweight design as well as specific design rules in terms of production processes and materials.

While conducting the research project HIPAT, funded by the German Federal Ministry of Education and Research (BMBF), the "Institut für Konstruktionstechnik", compiled a first collection of design rules. Based on Microsoft Excel, this collection of design knowledge can be applied in a limited way. The knowledge representation in Microsoft Excel offers a systematic structure and makes well-known programme functions applicable to design rules (see following Figure 3). The collection of design rules can be filtered with key topics:

- Functional Integration,
- Lightweight Design,
- Roll Forming,
- Tailored Rolled Blanks,
- Material.

no.	field	rules	examples and pictures	reference	release
1	integration of function	sum equal, integrable functions	 internet through the socket	Institute for Engineering Design	Institute for Engineering Design
2	integration of function	Integration of non directly integrable functions through time series arrangement	 wiper	Institute for Engineering Design	Institute for Engineering Design
3	integration of function	Integration through self-assistance principles	 radial sealing	Institute for Engineering Design	Institute for Engineering Design
57	roll profile	Dimension of the holes in the profile only from one edge (plate width variation and odd Coilstränge)		Schmitz Cargobull AG	Institute for Engineering Design
58	flexible sheet metal rolling	Maximum sheet thickness of 4mm		Muhr und Bender GmbH	Institute for Engineering Design

quick  
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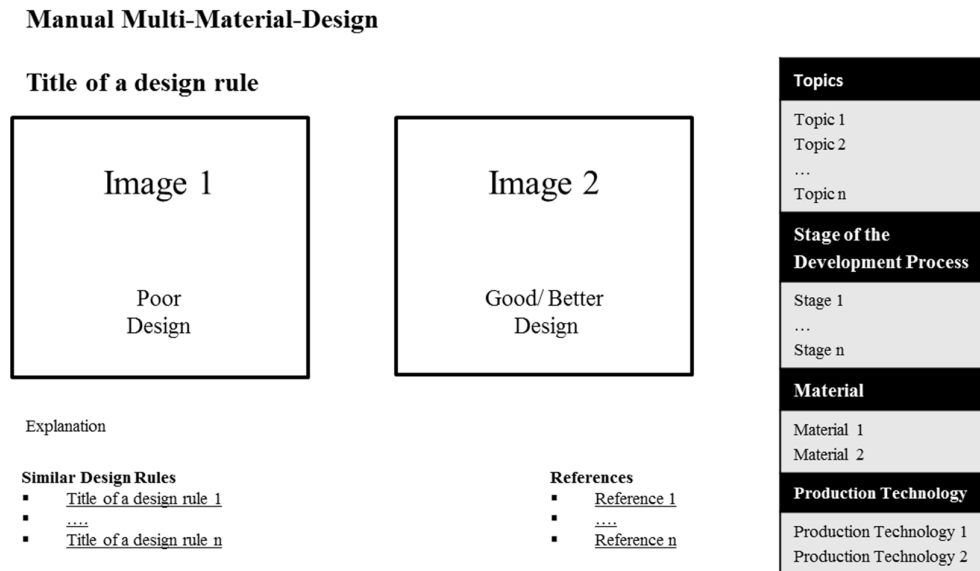
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**Figure 3. Detail of the structured design rules with a clear statement, the corresponding image and the references according to [Nehuis et al. 2011]**

Each design rule is defined with a clear statement, and added to a corresponding image and references. The simple defined instructions allow quick access to knowledge [Nehuis et al. 2011]. The images of the design rules also allow inexperienced designers to quickly understand complex situations [Mayer and Gallini 1990], [Salustri et al. 2008]. This helps to avoid unnecessary iterations reducing development costs and time.

By extending the design rules with new topics such as FRP, joining, forming and injection moulding, new challenges occur. At a certain point the number of design rules makes the original representation user-unfriendly for the new application in automotive design, especially in terms of multi-material-design. The majority of design rules must be assigned to up to four topics at the same time. In the end a simple approach to structuring the design rules is no longer advantageous. In addition, the complexity increases with the high number of design rules and its classification. This, in turn, reduces the

applicability of the "Manual Multi-Material-Design". Due to new complex topics such as fracture mechanics of FRP, a longer explanation must be provided though a quick access would enable the best outcome. This leads to the conclusion to transfer data into a high-performance data management system to benefit from new opportunities. Below mentioned figure shows a re-definition of the design rule layout with additional characteristics.



**Figure 4. Modified "Manual Multi-Material-Design"**

The design rules include:

- Title,
- Explanation,
- Pictures (Good and Poor example),
- Reference(s).

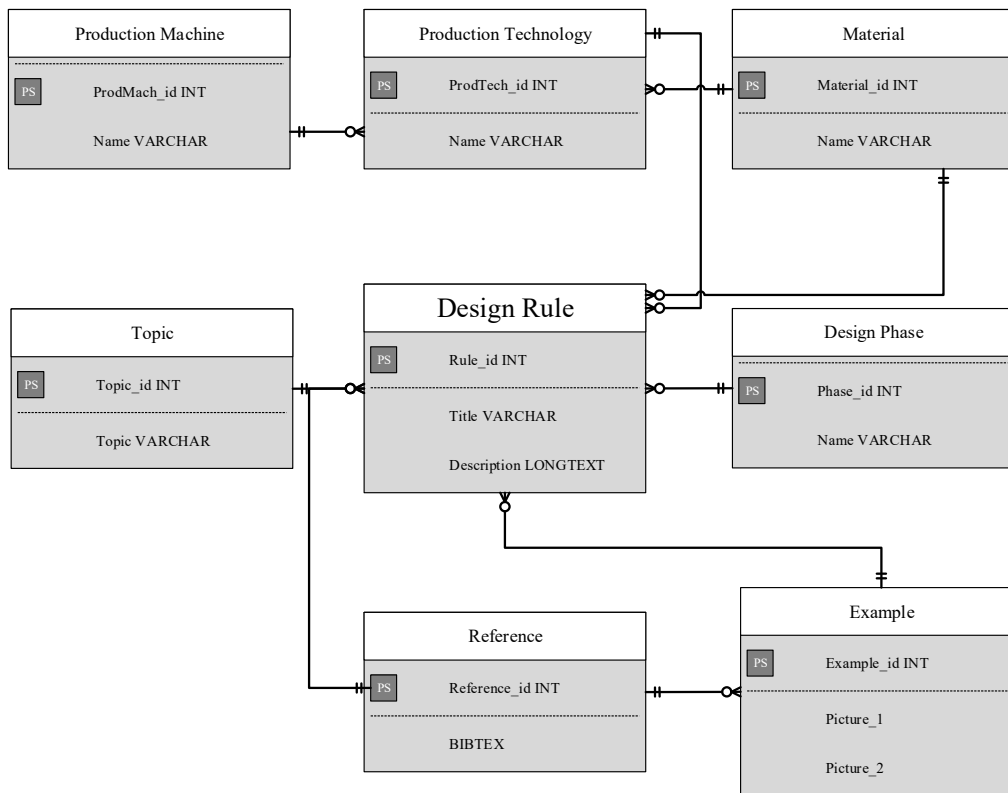
In addition, these design rules can be assigned to a sensible amount of topics, stages of the development process, materials and production technologies. This way the user is more likely to quickly find the most relevant design rules. Moreover, other design rules are suggested which are similar in terms of the assigned topic, stage of the development process, material and/ or production technology.

To achieve this layout, the necessary information is implemented into a state-of-the-art open source object-relational database system. It is scalable both, in the manageable quantity of data, and in the number of simultaneously accommodating users. The object-relational database offers a mathematical relation between the objects and allows to exploit useful techniques and theorems from set theory. In addition, it allows containers such as sets and lists, arbitrary user-defined datatypes as well as nested objects. This brings commonality between the application type systems and database type systems which removes any issue of impedance mismatch.

Figure 5 shows the Entity-Relationship-Model of design rules. Each defined rule has a unique ID, a title and a description. Moreover, a design rule is linked to other objects with a n:m relationship that helps the user to find relevant design rules for the development task.

Other possible objects are:

- Example,
- Reference,
- Topic,
- Design Phase,
- Material,
- Production Technology and
- Production Machine.



**Figure 5. Entity-Relationship-Model of the design rules**

In addition, the objects are linked to each other and therefore corresponding materials with a selection of production technologies. The design rules in production technology and production machines are crucial because the components' geometry and the available material combinations are depended on the production technology. Moreover, in terms of industrial application it is inevitable to take existing production machines into account as every production machine has its specific limitations in terms of overall component size and feasible dimensions.

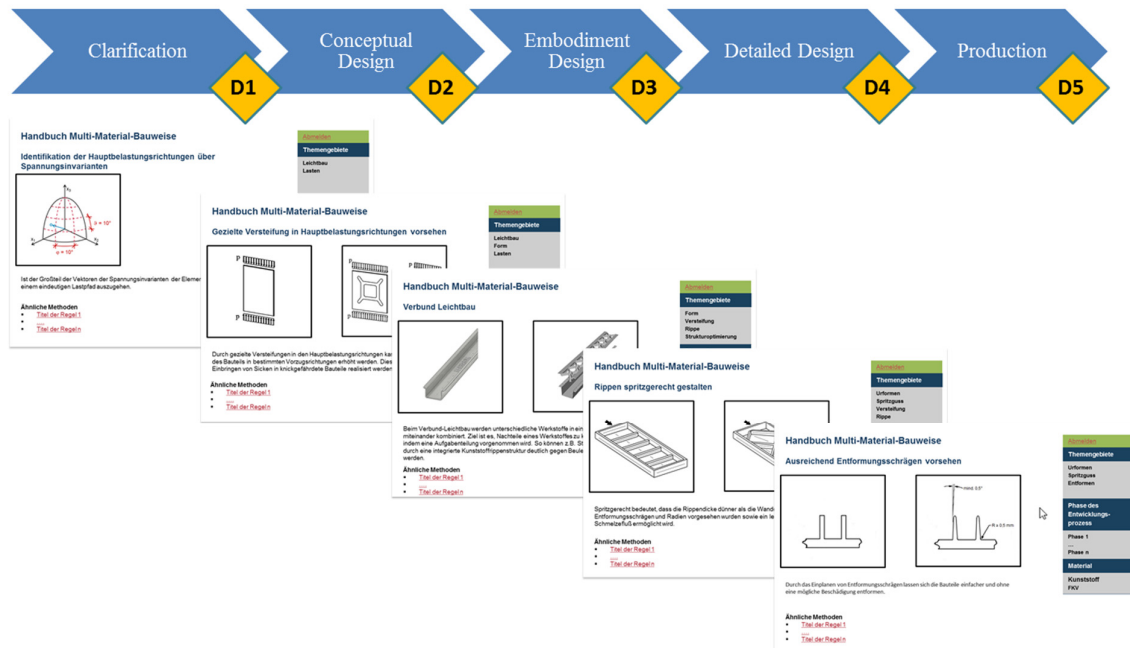
Firstly, the realised object-relational database system offers the possibility to find a design rule via different topics or with respect to the phase of the design process. Secondly, the user is able to find material-specific or production technology-specific design rules. Thirdly, a full text search is available. The correlation between design rules and the stage of the development process seems appropriate since some rules are more suitable for finding the best solution principle than others. Rules on lightweight design and functional integration are applied at early stages of the design process, when there is still little knowledge on the part design. Therefore, general statements are made which support, for example, the selection of an optimal solution principle [Nehuis et al. 2011]. Furthermore, there are design rules for later stages of product design in terms of design for manufacturing and numerical simulation of components.

The presented object-relational database is accessible through a webpage. The designer is able to browse through the design rules and search for specific design rules. In addition, the user can place a request for design rules based on key words (e.g. reinforcement, stiffener, demoulding) with an optional filtering based on the above mentioned topics and phases of the development process. Afterwards, the web page shows a list of matching design rules. At this point, the web page only shows the titles of the matching design rules. The complete information is displayed after choosing one design rules. Based on the linking of the stored design rules, further design rules are suggested which are similar in terms of topics, materials or key words.

By now, the implementation is prototypic and available at the authors' department. The knowledge management system is being tested by researchers and graduate students working in the field of automotive lightweight design and multi-material-design.

## 4. Showcase

In the following section the authors show how the described "Manual Multi-Material-Design" can be used for developing automotive components in multi-material-design with respect to a generalised automotive development process. This process is defined in coordination with the respective project partners and is representative for the development in the automotive industry. The development process is divided into five phases with a decision-making in the end (Figure 6).



**Figure 6. Use of design rules in the automotive development process**

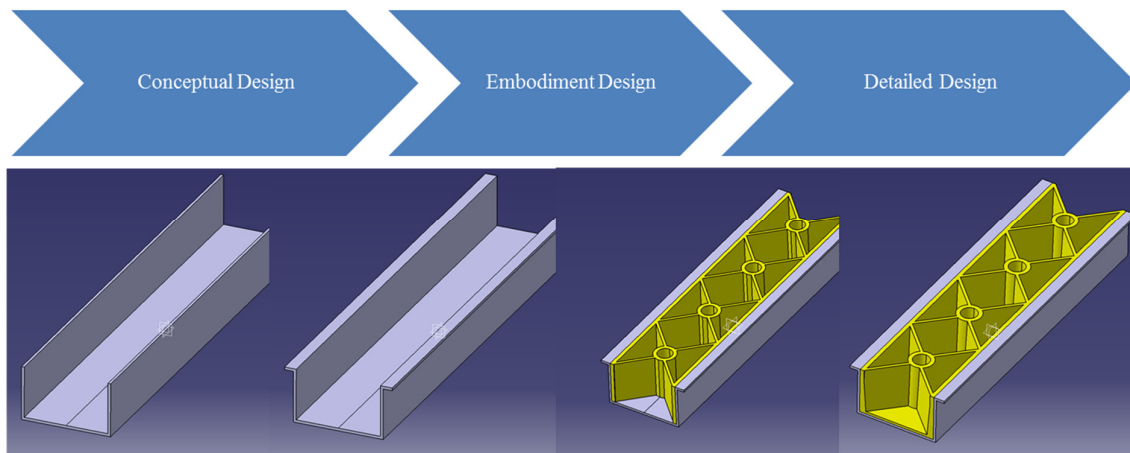
The requirements are determined in the course of clarifying the development task. A lot of data are gathered from predecessor vehicle projects and components. A major information for successful lightweight design, either with conventional design strategies or with multi-material-design, are the load-paths. The "Manual Multi-Material-Design" offers different approaches to identifying load-paths according to the literature [Durst 2008]. One suitable approach is based on FEM output data from predecessor projects. By analysing the invariants of the stress deviator tensor one can identify these elements with similar invariants and set up a clear load-path. This analysis needs to be applied for each relevant load-case and the results superposed.

Based on the knowledge of the found load-paths, the conceptual design is supported by design rules for choosing the right material distribution and exploiting the advantages of multi-material-design. A reinforcement with regard to the main load-path allows a reduction of the wall thickness or the choice of material of lower quality (e.g. high-strength steel instead of ultra-high-strength steel). Moreover, the reinforcement can be achieved by different solution principles such as ribs, unidirectional composite tapes or injection moulded stiffeners. In addition, the design rules regarding functional integration should be used during conceptualisation for providing the designer with inspiration for light and innovative designs.

In terms of embodiment design, additional and more detailed design rules can be applied. Typical design rules give information on wall thicknesses, manufacturable geometries with respect to the chosen manufacturing technology or the mechanical behaviour. One design rule is applied to the shown example (Figure 7) and suggests the flanging of edges of open profiles for increased buckling load and stability. In case of a concept in multi-material-design, the joining technology is crucial as well. Therefore, there are design rules provided, considering mechanical and adhesive joining. Beyond that, data is included



regarding the geometry of manufacturable undercuts which improve the mechanical performance. The shown concept uses injection stiffeners for reinforcing the structure. As a result, the engineer is able to define an advantageous stiffener design with respect to an efficient injection moulding process.



**Figure 7. Application of the "Manual Multi-Material-Design" on a representative academic example**

Within detailed design, the geometry is optimised by mechanical performance and manufacturing. Rules for an efficient use of CAA-tools such as finite element method are provided as well. These rules include meshing strategies, decision support for choosing proper element types, failure criteria for both, materials, as well as joining elements, and approaches for computer aided optimisation. In the above-shown example, detailed design rules for adequate drafting angles for demoulding are applied.

## 5. Conclusions and outlook

This paper explains the need for Knowledge Management Systems for automotive lightweight design and multi-material-design. The explained approach is based on design rules distributed by an object-relational database system. The presented application of the "Manual Multi-Material Design" shows the general applicability on automotive development tasks.

In the future, the prototypic system will be published and free accessible on a webpage. In addition, the usability of the system is validated in the course of ongoing research by the project partners. Besides that, the authors will extend the available design rules and will implement further algorithms for identifying similar design rules to gain linked knowledge. A possible desired extension is the direct connection between the database and CAD software and product data management. This allows to work more comfortably and increases the acceptance of the system. The connection to product data management offers the opportunity to illustrate design rules with 3D product data where they were applied successfully.

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